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Use of reflectance band ratios to estimate suspended and dissolved matter concentrations in estuarine waters

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In the Tamar estuary (south-west UK), the concentrations of coloured dissolved organic and suspended (total, organic and inorganic) matter were measured and related to *in situ* hyperspectral remote-sensing reflectance (R_{rs}) measurements. A simple method was used to determine the R_{rs} signal from underwater optical measurements, in order to avoid any surface reflection effects. As previously observed in other estuaries, a large correlation was obtained between the $R_{rs}(850\,nm)/R_{rs}(550\,nm)$ ratio and total suspended matter concentration. The same R_{rs} ratio was also highly correlated to the inorganic suspended matter concentration. The corresponding relationships are linear. The $R_{rs}(400\,nm)/R_{rs}(600\,nm)$ ratio correlates with the coloured dissolved organic matter concentration, according to a power law regression. These relationships, which appeared to be invariant during the summer period (June–September) and valid for the whole estuary, may be applied to airborne remote sensing data to map the tidal movements of turbidity in the estuary.

1. Introduction

Estuaries are highly dynamic environments. They represent a major interest in terms of transport of matter from upland basins to the ocean. Airborne remote sensing data are useful to map the water turbidity in such areas. However, they require robust quantification algorithms that include conversion of the water-leaving signal into concentrations of the water constituents. In this domain, recently obtained results are encouraging: the models fitted can be used to predict suspended solids (e.g. Doxaran *et al.* 2002, 2003) and dissolved organic matter (e.g. Bowers *et al.* 2000, 2004, D'Sa and Miller 2003) concentrations from above-water optical measurements.

The objective of this study is to develop such models for the compact airborne spectrographic imager (CASI) in the Tamar estuarine waters (south-west UK).

Field optical measurements of the water-leaving radiance signal, L_w, and downwelling irradiance signal just above the water surface, $E_d(0+)$, lead to the determination of the remote-sensing reflectance signal (R_{rs}, in sr^{-1}) defined as (Mobley 1994):

$$R_{rs}(\lambda) = \frac{L_w(\lambda)}{E_d(\lambda, 0^+)}, \tag{1}$$

where λ (in nm) is the wavelength.

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The R_{rs} signal is related to the total, organic and inorganic suspended matter concentrations within surface waters, then to the dissolved organic matter concentrations.

2. Data and analyses

Data were collected in 2003 in the Tamar estuary where a maximum turbidity zone (MTZ) is generally developed in the upstream part (Uncles *et al.* 1985). The concentration of suspended solids (essentially silts, clays and organic matter) is generally low in the downstream part (2–10 mg l^{-1}) as opposed to the upstream part (100–1000 mg l^{-1}) (e.g. Uncles and Stephens 1993, Tattersall *et al.* 2003).

Field optical measurements were carried out in June, August and September (respectively 41, 14 and 21 stations) along transects covering the whole estuary, or at a fixed station in the upstream part (table 1). In each station, water samples were collected from surface waters and analysed for suspended and dissolved material, then related to optical (R_{rs}) measurements.

Water samples were filtered on pre-ashed and pre-weighed Whatman GF/F glass-fibre filters. Filters were dried for 24 hours at 65°C, then weighed in order to determine the total suspended matter concentration ($TSMc$, in mg l^{-1}). Filters were then burned at 450°C for 4 hours to remove the organic part, and weighed again to estimate the particulate organic and inorganic content, then the organic and inorganic suspended matter concentrations ($OSMc$ and $ISMc$, in mg l^{-1}).

Immediately after collection, the water samples were filtered through Whatman Anodisc filters (pore size: 0.20 μm). The residual samples were collected in cleaned glass bottles and stored in a cool box prior to laboratory analyses; they were then allowed to reach the ambient temperature before measuring their absorbance spectrum ($abs_y(\lambda)$, $400<\lambda<700$ nm) with a UNICAM single beam spectrophotometer (using a 5 cm path-length cuvette). An absorbance spectrum of Milli-Q water ($abs_{MQ}(\lambda)$) was recorded before and after the sample measurement, in order to check the stability of the lamp. The absorption coefficient of coloured dissolved organic matter (CDOM), $a_y(\lambda)$, was calculated as (Hooker *et al.* 1999):

$$a_y(\lambda) = 2.303\left[abs_y(\lambda) - abs_{MQ}(\lambda)\right]/l, \quad (2)$$

where l (in m) is the path-length of the cuvette.

The CDOM concentration is generally expressed as the absorption coefficient at 440 nm ($a_y(440)$) (e.g. Kirk 1994, Mobley 1994).

Table 1. Details of the data collected in the Tamar estuary in June, August and September 2003.

Date	Location	Stations TSM/CDOM	Sky conditions
23 June 2003	Transect mouth—upstream	12/10	Clear sky
24 June 2003	Transect mouth—upstream	13/0	Clear sky
25 June 2003	Upstream (fixed station)	4/0	Covered sky
26 June 2003	Upstream (fixed station)	6/0	Covered sky
27 June 2003	Upstream (fixed station)	9/0	Clear sky
05 August 2003	Transect mouth—upstream	14/14	Clear sky
03 September 2003	Transect mouth—upstream	11/11	Covered sky
04 September 2003	Transect mouth—upstream	10/10	Clear sky

Optical measurements were carried out using a Trios-RAMSES multispectral (350–950 nm) radiometer (7° field-of-view; 3.3 nm spectral resolution). The underwater upwelling radiance signal, L_u, was measured with the sensor pointing to nadir, at different depths (typically 0.02, 0.10, 0.15 and 0.20 m). A vertical bar was used to accurately control the depth of the sensor. The attenuation of L_u with increasing water depth appeared to be strongly influenced by the water turbidity (*TSMc*) (figure 1). In all stations, independent of wavelength and water turbidity, the attenuation was well described by an exponential law (coefficient of determination higher than 0.98) (Doxaran *et al.* 2004).

The upwelling radiance just beneath the water surface, $L_u(0^-)$, was determined according to (Hooker *et al.* 1999):

$$L_u(\lambda, z) = L_u(\lambda, 0^-)\exp[-K_L(\lambda)z], \tag{3}$$

with z the water depth and K_L (in m^{-1}) the attenuation coefficient for radiance. L_w was finally determined according to (Morel 1980):

$$L_w(\lambda) \approx 0.544\, L_u(\lambda, 0^-). \tag{4}$$

The sensor was pointed vertically towards a white square spectralon target (Labsphere ref. SRT-99-050, reflectance value of 99%) when measuring the downwelling radiance signal L_d. Three L_d spectra were recorded before and after the underwater measurements, in order to observe the incident light variations. Assuming the spectralon plate of reflectance R_g to be near-lambertian, E_d was determined as:

$$E_d(\lambda) = \pi L_d(\lambda) / R_g(\lambda). \tag{5}$$

The R_{rs} signal was finally determined according to equation (1).

3. Results and discussion

The measured *TSMc* gradually increased from the mouth (minimum of $3\,mg\,l^{-1}$) to the upstream part of the estuary (around $100\,mg\,l^{-1}$ and up to $300\,mg\,l^{-1}$). The observed mean concentration was $44\,mg\,l^{-1}$.

In the upstream part, where the MTZ ($TSMc > 100\,mg\,l^{-1}$) was located, the particulate organic fraction was typically 10 to 20% of the total suspended matter. In the central part of the estuary ($10 < TSMc < 100\,mg\,l^{-1}$), it varied from 20 to 30%, and reached maximum values in the downstream part and near the mouth (30 to 50%). Such observations are in agreement with previous observations (Uncles and Stephens 1993).

Strong variations of CDOM concentrations were also observed along the estuary. $a_y(440)$ was low (from 0.1 to $0.4\,m^{-1}$) near the mouth, progressively increased in the downstream then central parts, and reached maximum values (up to $1.9\,m^{-1}$) in the upstream part. These observations clearly indicate that the river is the main origin of CDOM in the estuary, and are in agreement with the dissolved organic carbon dynamics in the estuary described by Miller (1999).

R_{rs} was first related to *TSMc*. Based on previous results obtained in sediment-dominated estuarine waters, robust relationships can be established between *TSMc* and an R_{rs} ratio between near-infrared and visible wavelengths (Doxaran *et al.* 2002, 2003). These results are confirmed in the Tamar estuary. A linear relationship ($R^2 = 0.96$) was obtained between *TSMc* and the $R_{rs}(850)/R_{rs}(550)$ ratio (figure 2), including all measurements carried out from June to September. It can be directly compared to the relationship established in the Gironde estuary during the 2000 and

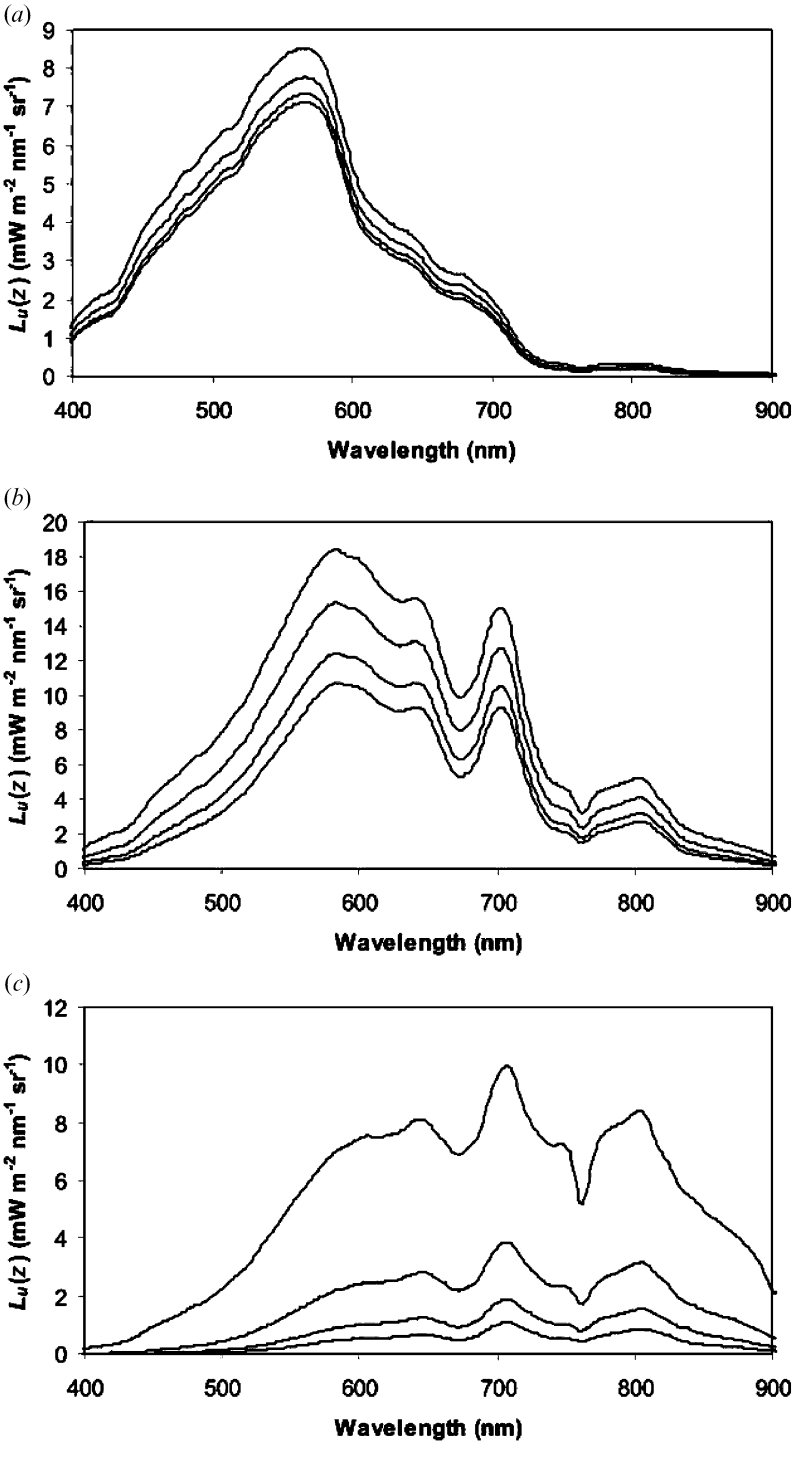

Figure 1. Examples of L_u spectra measured at different water depths (from top to bottom: 0.02, 0.10, 0.15 and 0.20 m). (a) 24 June 2003 at 10:50 U.T. ($TSMc = 7\,mg\,l^{-1}$). (b) 24 June 2003 at 14:25 U.T. ($TSMc = 45\,mg\,l^{-1}$). (b) 27 June 2003 at 14:18 U.T. ($TSMc = 303\,mg\,l^{-1}$).

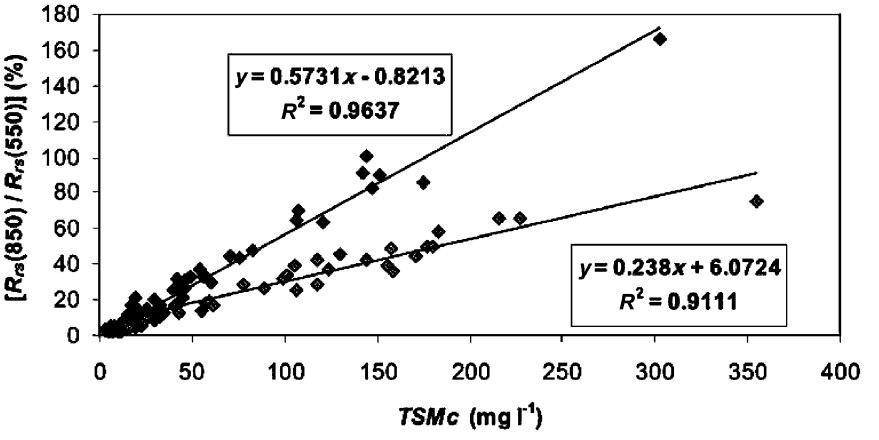

Figure 2. Ratio of reflectance, $R_{rs}(850\,nm)/R_{rs}(550\,nm)$, plotted against *TSMc* in the Tamar estuary (black points). Comparison with results obtained in the Gironde estuary (grey points) by Doxaran *et al.* (2002). The corresponding equations and coefficients of determination of the linear regressions are indicated.

2001 summer periods (Doxaran *et al.* 2002) (figure 2). Both relationships are linear but present different slopes, resulting from different inherent optical properties, thus from different characteristics of suspended and dissolved material.

The respective influences of the organic and inorganic suspended matter on the relationship obtained in the Tamar can be assessed by plotting $R_{rs}(850)/R_{rs}(550)$ as a function of *ISMc* and *OSMc*. In both cases, a correlation is observed but results clearly show the predominant influence of the inorganic material (figure 3). The established relationships may be used to quantify both the organic and inorganic suspended matter.

Recent studies showed that linear relationships can be established between $a_y(440)$ and the ratio of reflectance in the red (e.g. 670 nm) and one other visible wavelength (e.g. 490 nm) (Bowers *et al.* 2000, 2004), provided the effect of suspended particles on the optical signature is small compared to that of CDOM. According to D'Sa and Miller (2003), these relationships follow a power law in sediment-dominated coastal waters. This latest statement is confirmed in the Tamar when considering a reflectance ratio between red (600 nm) and blue (400 nm) wavelengths (figure 4). The established relationship includes all the measurements carried out from June to September 2003 with a large coefficient of determination ($R^2=0.89$). Thus, it appears to be invariant during the summer period and may be used to estimate CDOM concentrations from R_{rs} measurements.

4. Conclusion

In the Tamar estuary, empirical relationships have been established between the R_{rs} signal and the concentration of water constituents: suspended matter (total, organic and inorganic), and CDOM.

A large correlation ($R^2=0.96$; linear regression) was obtained between the near-infrared (850 nm) to visible (550 nm) R_{rs} ratio and *TSMc*. Results previously obtained in the Gironde and Loire estuaries (Doxaran *et al.* 2002, 2003) are thus extended to a third quite different estuarine environment. In the Tamar, the obtained relationship is essentially governed by the inorganic particles, though

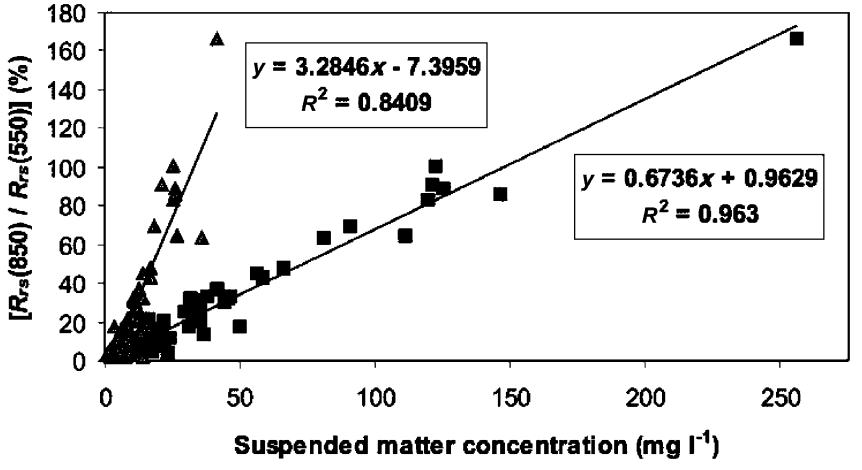

Figure 3. Ratio of reflectance, $R_{rs}(850\,nm)/R_{rs}(550\,nm)$, plotted against *ISMc* (black squares) and *OSMc* (grey triangles). The corresponding equations and coefficients of determination of the linear regressions are indicated.

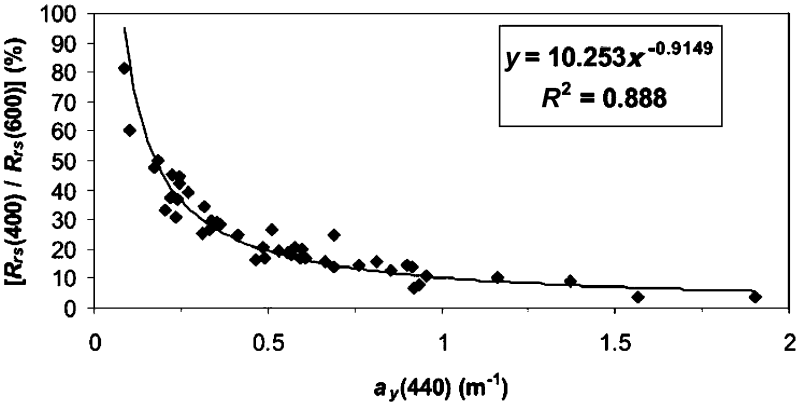

Figure 4. Ratio of reflectance, $R_{rs}(850\,nm)/R_{rs}(550\,nm)$, plotted against CDOM concentrations. The equation and coefficient of determination of the power law regression are indicated.

the particulate organic content varies from 10% to 50%. Thus, the same R_{rs} ratio may be used to quantify the total, organic and inorganic suspended matter. When considering an R_{rs} ratio between two visible wavelengths (400 and 600 nm), a large correlation (R^2=0.89; power law regression) was obtained with the CDOM concentration. Such a result is in agreement with the observations of D'Sa and Miller (2003) in coastal waters influenced by high freshwater discharges.

The relationships established in the Tamar appeared to be invariant during the summer period (June–September) and valid for the whole estuary. Further research will involve applying the relationships to multi-spectral airborne data (CASI) flown during this period, which will be corrected for atmospheric effects (Lavender and Nagur 2002). Flying CASI several times during a day, and therefore collecting data during the different phases of a tidal cycle, will provide important spatial information on the tidal behaviour of TSM and CDOM concentrations within

the surface waters of the estuary. This information cannot be obtained from point sampling using a boat and can be combined with physical modelling to provide a greater understanding of sediment and chemical transport within the estuary.

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